1 Current Status of Nuclear Parton Densities and Fragmentation Functions

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1.1 Introduction

In spite of the remarkable phenomenological success of QCD as the theory of strong interactions, a detailed understanding of the role of quark and gluon degrees of freedom in nuclear matter is still lacking and poses great challenges for the theory. Ever since the discovery that quark and gluons in bound nucleons exhibit momentum distributions noticeably different from those measured in free or loosely bound nucleons [1] more than two decades ago, the precise determination of nuclear parton distribution functions (nPDF) has attracted growing attention, driving both increasingly accurate and comprehensive nuclear structure functions measurements [2] and a more refined theoretical understanding of the underlying physics.

The precise knowledge of nPDFs is not only required for a deeper understanding of the mechanisms associated with nuclear binding from a QCD improved parton model perspective, but is also a crucial input for the theoretical interpretation and analyses of a wide variety of ongoing and future high energy physics experiments, such as, for instance, heavy ion collisions at BNL-RHIC [3], proton-nucleus collisions to be performed at the CERN-LHC [4], or neutrino-nucleus interactions in long baseline neutrino experiments [5]. Consequently, the kinematic range and the accuracy at which nPDFs are known has evolved into a key issue in many areas of hadronic and particle physics.

From the point of view of perturbative QCD (pQCD), the extraction of nPDF can be performed in close analogy to what is routinely done for free nucleons: they are considered as non-perturbative inputs, to be inferred from data, whose relation to the measured observables and their energy scale dependence can be computed order by order in perturbation theory. Although one can not discard potentially larger higher-twist or power corrections than in the case of free nucleons, or non-linear nuclear recombination effects, standard QCD factorization and universality of nPDFs are found to hold to a very good approximation in the kinematical range covered by present experiments.

At variance with PDFs for free nucleons, which, driven by the demand for increasingly precise predictions of standard model "background" processes for the LHC, have attained an impressive degree of accuracy and refinement recently, extractions of nPDFs are done at a considerably lower level of sophistication. Not only the number, variety, kinematical coverage, and precision of nuclear data are much more limited, but the precise parameterization of nPDFs is also much more involved as it depends not only on the energy scale Q and the parton's momentum fraction x but also on the size of the nucleus characterized by the atomic number A.

Similarly to modifications of PDFs in nuclei, the production of hadrons in the final-state is known to be affected when occurring in a nuclear environment. For example,

semi-inclusive deep-inelastic scattering (SIDIS) off large nuclear targets shows significant differences as compared to hadron production off light nuclei or proton targets [6, 7]. The origin of these medium effects, besides the well-known modification of PDFs in nuclei, which is not sufficient to explain them, have been attributed to a wide variety of mechanisms [8, 9], ranging from interactions between the nuclear medium and the seed partons before the actual hadronization takes place to interactions between the medium and the final-state hadrons as implemented in various pQCD and nuclear physics inspired models, respectively. Most of these models reproduce with different degree of success some features of the data, in spite of the very different approaches and ingredients.

The past few years have seen a significant improvement in the pQCD description of hadron production processes, and, more specifically, in the precise determination of vacuum fragmentation functions (FFs), including estimates of their uncertainties [10]. FFs carry the details of the non-perturbative hadronization process, factorized from the hard scattering cross section in the same way as for PDFs. The most important result of these studies is that the standard pQCD framework not only reproduces data on electron-positron annihilation into hadrons, but it describes with remarkable precision also other processes like semi-inclusive deep-inelastic scattering and hadron production in proton-proton collisions.

It is quite natural then to ask if pQCD factorization can be also generalized to final-state nuclear effects, i.e., to introduce medium modified or nuclear fragmentation functions (nFFs), and to assess how good such an approximation works or to determine where and why it breaks down. From theoretical considerations alone, the answer is, however, not obvious since on the one hand, interactions with the nuclear medium may spoil the requirements of the factorization theorems, but, on the other hand, any estimates of possible factorization breaking effects are strongly model dependent.

Within the factorization ansatz and like for nPDFs, nFFs should contain (factorize) all the non-perturbative details related to hadronization in a nuclear environment, would be exchangeable from one process to another (universal), and would allow for QCD estimates at any given order in perturbation theory in a well defined and unified framework. These features can be explicitly tested using data from an increasing but still limited number of experiments that have performed precise measurements of hadron production off nuclear targets, for instance, in SIDIS by HERMES [7] or in deuteron-gold collisions studied at RHIC [11, 12]. Both type of processes are compatible with a universal nuclear modification of the hadronization mechanism in the currently accessible kinematic regime. The inclusion of next-to-leading order QCD corrections and the possibility to use different observables have been proven to be crucial for an accurate parametrization of nFFs [13].

In addition to the primary goal of testing the factorization properties of nFFs and to constrain them from different data sets in a consistent theoretical framework (for further comparison with the different model estimates), a thorough analysis of nFFs also serves as a baseline for ongoing studies of hadron production processes in heavy ion collisions performed at RHIC and the LHC [14].

In the following, we present a brief summary of the current status of nPDFs and nFFs and outline limitations in the analyses imposed by the data available so far.

Thanks to its variable beam energy, the possibility to run with different nuclei, and the envisioned large luminosities, an EIC will add invaluable novel information both on nPDF and nFFs from studies of inclusive structure functions $F_{2,L}$ and SIDIS, respectively. It will extend the kinematic range toward lower values of x as well as higher scales Q, allow for a flavor separation of the quark sea, and to study the onset of non-linear saturation effects which eventually spoil the factorized pQCD approach.

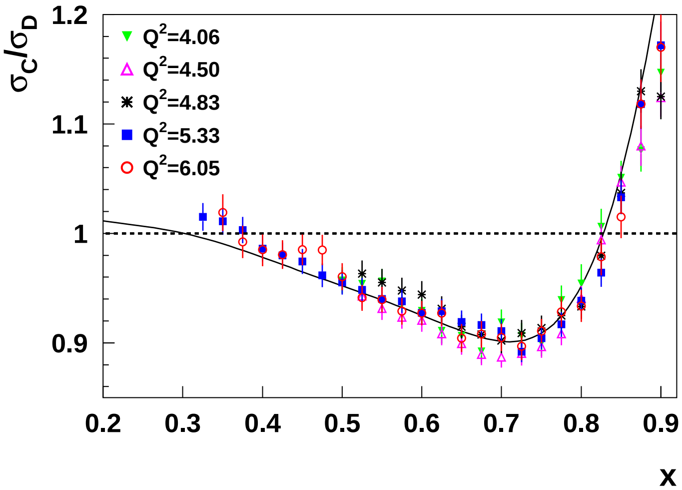

Figure 1: EMC effect and Fermi motion as measured at JLAB [15].

1.2 Status of Nuclear Parton Densities

The standard description of DIS processes off nuclear targets is customarily done in terms of the hard scale Q set by the virtuality of the exchanged photon and a scaling variable $x_A \equiv Q^2/(2p_A \cdot q)$, analogue to the Bjorken variable used in DIS off nucleons. Here, p_A is the target nucleus momentum, and, consequently, x_A is kinematically restricted to $0 < x_A < 1$, just like the standard Bjorken variable. Alternatively, one can define another scaling variable $x_N \equiv A\, x_A$, where A is the number of the nucleons in the nucleus. Under the assumption that the nucleus momentum p_A is evenly distributed between the nucleons $p_N = p_A/A$, this variable resembles the Bjorken variable corresponding to the scattering off free nucleons, $x_N \equiv Q^2/(2p_N \cdot q)$. However, in nuclear scattering context it spans the interval $0 < x_N < A$, by definition, reflecting the fact that a parton may in principle carry more than the average nucleon momentum.

In the most naive picture, parton distributions in a nucleus are simply given by the incoherent sum or superposition of the parton distributions in the Z protons and $(A - Z)$ neutrons that constitute the nucleus. In that case, the ratios between the structure functions or cross sections of two isoscalar nuclei (with the same proportion of protons and neutrons, such as carbon and deuteron) should be just proportional to the ratio of their respective number of nucleons (or to unity if we normalize the structure functions by the number of nucleons A).

If we take into account Fermi motion effects, one would expect that in the larger nuclei, the cross section extends up to larger x_N, so the rates should typically grow to larger than unity at high x_N. What the EMC experiment found was that in addition to this motion effect, there was a significant and quite unexpected frop in the rates between approximately $x_N \approx 0.3$ and $x_N \approx 0.7$. In Figure 1 we show a precise measurement performed at JLAB [15] recently that illustrates both effects.

Later on, it was found that the situation was even worse for the naive picture outlined above, because at lower x_N values, the rates showed again non-trivial patterns of suppression and enhancement. These effects are called shadowing and anti-shadowing, respectively. The phenomenon has been measured at different Q^2 and basically persists at higher Q^2 but

with a particular dependence, specific for each x_N region. In the following years different explanations, mechanisms, and QCD inspired models have been put forward.

From the point of view of pQCD and a factorized approach, the description of nuclear DIS can be viewed as follows. In a DIS processes off a nuclear target, we also have a hard momentum scale Q that allows one to factorize the measured cross section into a point-like partonic cross section and non-perturbative parton densities, characteristic of partons seen in that nucleus. These "effective" parton densities factorize and encode all the non-perturbative information, including the details about the nuclear structure, and every mechanism, interaction, or effect we can imagine. Since the hard partonic cross sections are just the same as those appearing in the factorization for free nucleons, the nuclear parton densities will evolve with scale in the same way as ordinary parton densities. For similar reasons, the approach could be extended to higher orders.

What is clearly not obvious within this line of reasoning is why, or how, one could split the non-perturbative effective nuclear parton density into a piece containing only the effects related to quarks and gluons belonging to single nucleon from those related to the nucleons bound in the nuclei. No field theoretical tool gives us a precise prescription of how to achieve this. It is important to keep in mind, that even in lepton-nucleon scattering, standard PDFs are not just naive probability densities; they are non-trivial objects, perfectly well defined though, but depend on the choice of factorization scheme and contain other ingredients such as gauge links.

What can done, of course, is to follow a program of global QCD analyses completely analogous to the one carried out for PDFs, i.e., to extract the nPDFs and their A dependence from data. In doing so one can explore if the basic properties of factorization and universality still hold in a nuclear environment. The first QCD extractions of nPDFs defined in this way were done at the end of the 90's by two pioneering groups who performed LO analyses of nuclear DIS data (EKS98, HKM01) [16, 17]. Previous to that, people estimated and compared ratios of structure function for different nuclei A, and also defined x_N, Q^2, and A-dependent modification factors, typically the same for all the parton species, in some cases including evolution effects, but not quite like one would do in a modern pQCD fit.

When introducing nPDF, the usual approach was to propose a very simple relation between the parton distribution of a proton bound in the nucleus, f_i^A, and those for free protons f_i,

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0^2, A, Z)\, f_i(x_N, Q_0^2), \tag{1}$$

in terms of a multiplicative nuclear correction factor $R_i(x_N, Q^2, A, Z)$, specific to a given nucleus (A, Z), parton flavor i, and initial energy scale Q_0^2. Such a description is convenient since the ratio $R_i(x_N, Q^2, A, Z)$ compares directly the parton densities with and without nuclear effects, and is closely related to the most common nuclear DIS observables, which are the ratios between the nuclear and deuterium structure functions. However, this is not the best suited way to parameterize the effects in the intermediate steps of the analysis, nor necessarily the best alternative for extending the analysis to higher orders of QCD in an efficient way.

In Ref. [18] the much more adequate alternative to relate nPDFs to standard PDFs by means of a convolution was introduced. The convolution approach implements straightforwardly effects related to rescalings or shifts in the parton's momentum fraction due to interactions with the nuclear medium. In addition, convolution integrals are the most natural language for parton dynamics beyond the LO and allow for the straightforward application of the Mellin transform techniques, convenient for a numerical fast and accurate

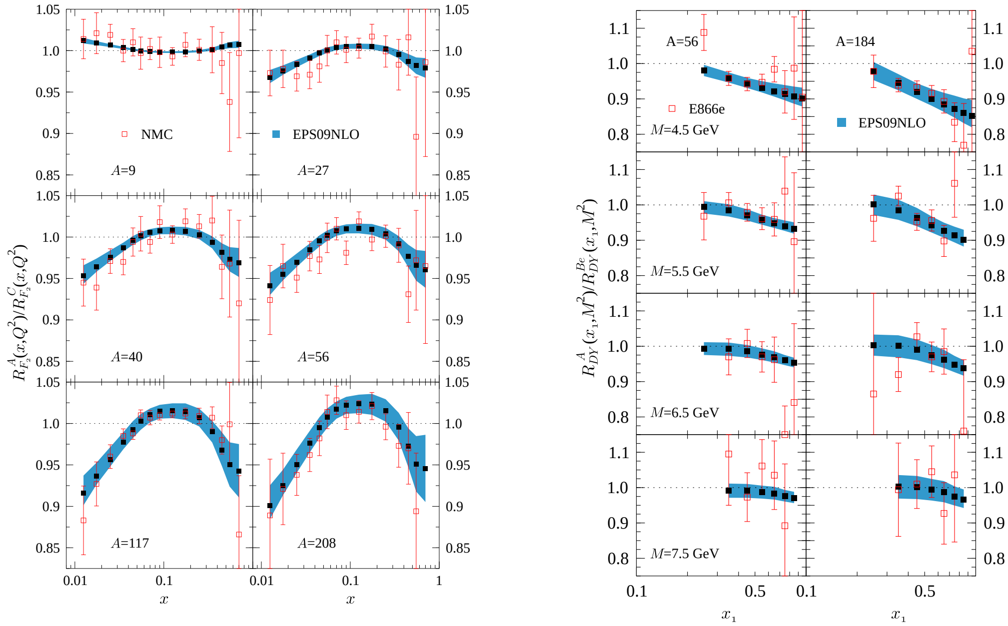

Figure 2: Quality of the fit to nuclear DIS and Drell-Yan data; taken from Ref. [22].

computation of the scale dependence of PDFs and relevant cross section estimates.

Following the developments for standard PDFs, nPDFs analyses subsequently incorporated various improvements such as a consistent NLO framework (nDS) [18], a thorough uncertainty analysis (HKN04 LO) [19], and periodical updates of the different sets in order to incorporate new data (EKPS07 LO) [20], and extensions to NLO accuracy (HKN07 NLO, EPS09 NLO) [21, 22]. In the latest sets of nPDFs [22, 23] particular attention has been paid to the possible impact of dAu collision data from RHIC and neutrino deep inelastic scattering data on the global fits. A typical comparison to nuclear DIS and Drell-Yan data is shown in Fig. 2.

It is worth noticing that the inclusion of dAu data in nPDFs fits, although neglecting any nuclear modifications in the hadronization process, leads to significantly larger gluon shadowing and antishadowing as it has been pointed by [22]. The same data, however, can be described with much more moderate nuclear gluon PDFs, but including medium modified nFFs [13].

Regarding the impact of neutrino data, Schienbein et al. [23] claim that within their analysis it is not possible to reproduce simultaneously the trend of the data coming from electromagnetic nuclear DIS and some observables derived from neutrino DIS measurements. Of course, these conclusions are reached under rather stringent assumptions such as a very specific parameterization for nuclear effects and those implicit in the derivation of the neutrino DIS rates to deuteron, which have not been actually measured yet. On the other hand, using the EPS09 analysis and neutrino DIS data, Paukkunen and Salgado [24] find no traces of such tension, besides some energy dependent fluctuations in the NuTeV data. A typical comparison to neutrino data is given in Fig. 3.

Different recent extractions of nPDFs are shown in Fig. 4. A general shortcoming of all present fits is, that independent nuclear modification factors can be determined for gluons, valence, and sea quarks only, without distinguishing different flavors. Also, present fixed-

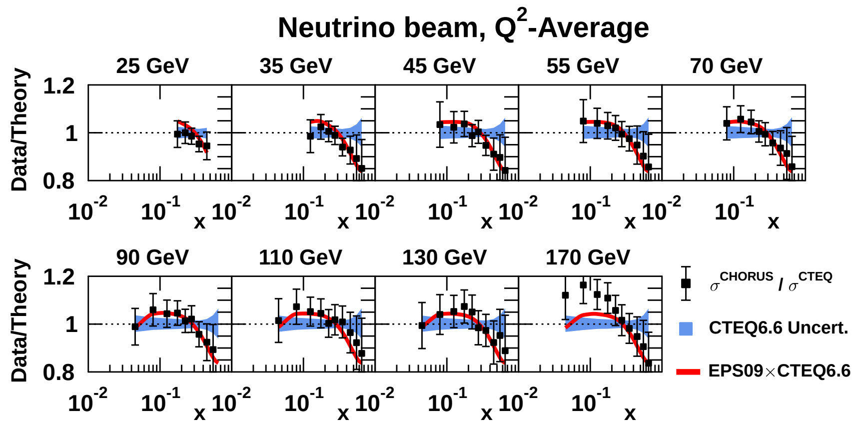

Figure 3: Comparison to neutrino data; taken from Ref. [24].

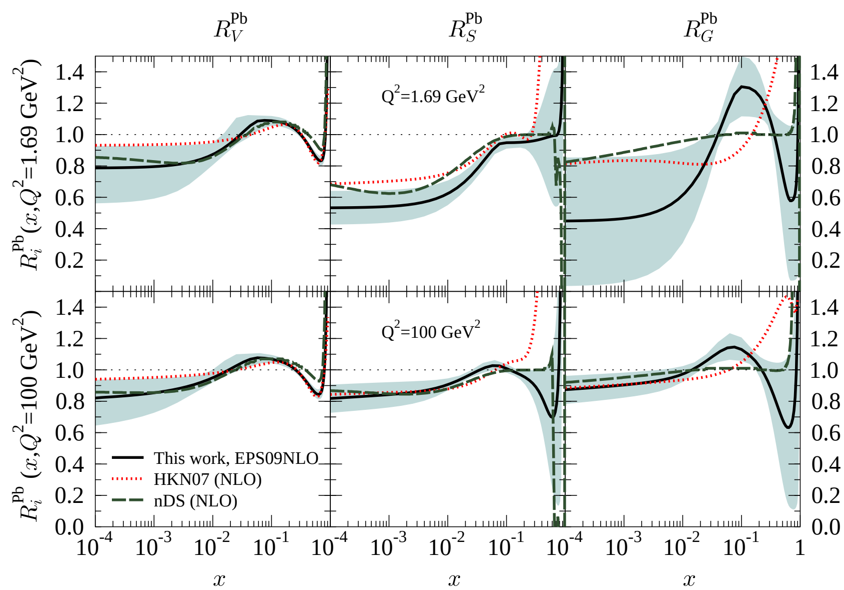

Figure 4: Comparison between different sets of nPDFs from [25].

target data do not constrain nPDFs below about $x_N \simeq 0.01$, and the curves shown at smaller values of x_N are mere extrapolations. Uncertainties on nPDFs are large, in particular for the nuclear gluon distribution. There is clearly a need for more precise data covering also the small x_N region.

1.3 Medium Modified Fragmentation Functions

Even though nuclear effects in the hadronization process have been known to be significant for quite some time, only recent experiments have become precise enough and selective from a kinematical point of view to allow for more detailed and quantitative studies.

Specifically, the HERMES collaboration has performed a series of measurements on different nuclear targets, with identified charged and neutral pions, kaons, and (anti)protons in the final-state [7]. The data are presented as distributions in the relevant kinematical variables, such as the hadron momentum fraction z and the photon virtuality Q^2, which both are used to characterize fragmentation functions, as well as the virtual photon energy ν, that can be related to the nucleon momentum fraction x carried by initial-state parton. Large hadron attenuation is found which increases with A.

In order to minimize initial-state medium induced effects, which in a factorized pQCD approach should be contained solely in the nPDFs, the data are presented as ratios of hadron multiplicities for heavy nuclei A and deuterium d. The cancellation of initial-state nuclear effects would be exact in a LO approximations where medium induced modifications to the PDFs could be represented by a single multiplicative factor irrespective of the parton flavor. Even though the different parton species are known to require different, non-trivial modifications, these differences get diluted, and even at NLO accuracy, they cancel in the ratio to a very good approximation.

Single-inclusive identified hadron yields obtained in dAu collisions at mid-rapidity at BNL-RHIC are another source of information on nuclear modification effects in the hadronization process. These measurements are often seen as "control experiments" associated with the heavy-ion program at RHIC to explore the properties of nuclear matter under extreme conditions. However, in view of the evidence for strong medium induced effects in the fragmentation process found in SIDIS, dAu data are also of a particular relevance for extracting nFFs and testing the assumed factorization and universality properties. Surprisingly, instead of the pronounced hadron attenuation observed in nuclear SIDIS data, the dAu to pp ratios show a curious pattern enhancement and suppression depending on p_T .

Assuming that factorization holds also for nFFs, one can use all of these data with identified hadrons in the final-state in a global QCD fit to extract nFFs. Rather than fitting the nFFs from scratch, which would take as many parameters as the standard (or vacuum) FFs, plus some more to represent the nuclear A dependence, it was proposed in Ref. [13] to relate the medium modified fragmentations to the standard ones in a convolution approach with a very simple ansatz for the weight functions. The fits gives a very good description of the full kinematic dependence of the HERMES data as can be seen in Fig. 5 while an approach which ignores all final-state nuclear effects clearly fails.

It is interesting to notice that there seems to be no visible conflict between the standard Q^2 dependence assumed for the nFFs and the data. In this respect, there have been many interesting suggestions and model dependent calculations at the LO level, motivating the use of medium modified evolution equations. However, in the range of Q^2 covered by present SIDIS and dAu data, there is no evidence for any significant departure from standard time-like evolution equations [26].

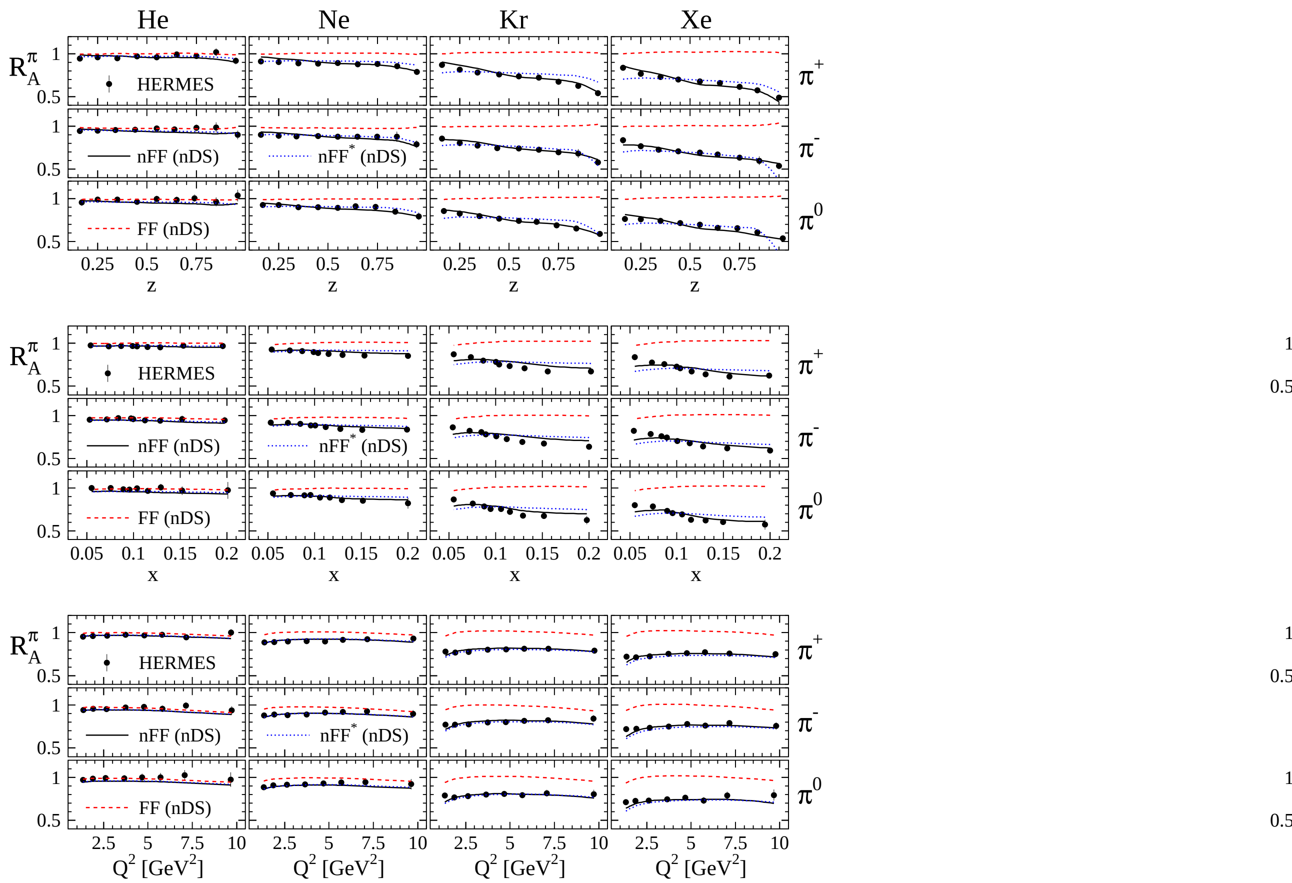

Figure 5: Quality of the nFF fit to nuclear SIDIS data from HERMES.

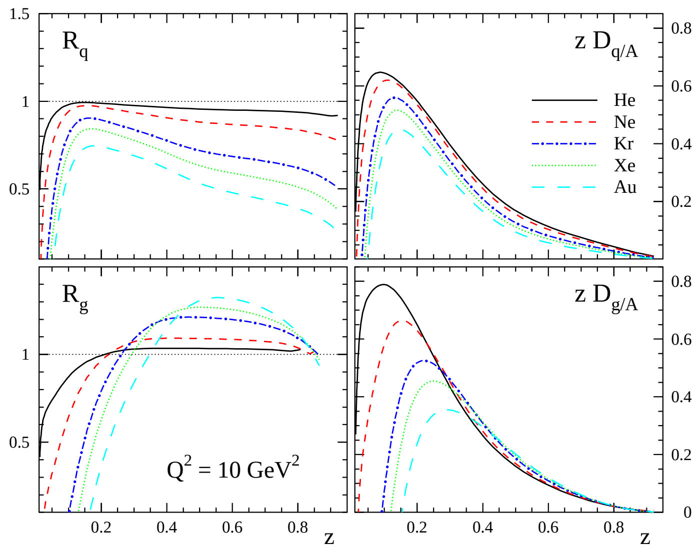

Figure 6: Ratios of medium modified and standard FFs.

The same set of nFFs that account for nuclear modification in SIDIS also reproduce the main features of the dAu data from RHIC. The peculiar p_T dependence of the effects is found to come from an interplay between quark and gluon fragmentation as a function of p_T in the hadron production cross section.

The resulting nFFs and the corresponding ratios to the standard DSS FFs, can be seen in Fig. 6 for various nuclei at. The pattern of medium induced modifications is rather different for quarks and for gluons. The dominant role of quark fragmentation in SIDIS leads to a suppression, i.e., $R_q^\pi < 1$, increasing with nuclear size A as dictated by the pattern of hadron attenuation found experimentally. The enhancement of hadrons observed in dAu collisions for $p_T \approx 10\,\mathrm{GeV}$, along with the dominant role of gluon fragmentation at low values of p_T explains that $R_g^\pi > 1$ for $z \to 0.2$. Below $z \simeq 0.2$, where all the data used in the fit have very limited or no constraining power, both quark and gluon nFFs drop rapidly. For the time being, the behavior in this region could easily be an artifact of the currently assumed functional form for the parameterization.

1.4 Conclusions

In the last few years our knowledge on the way that both parton densities and fragmentation probabilities are modified in a nuclear environment have improved significantly. Different studies performed so far have clearly demonstrated that pQCD factorization and universality are extremely good approximations within the precision of the data available. Although the uncertainties and differences between different QCD global analysis are still large, the availability of more data for different processes, and their subsequent inclusion in the analyses will certainly help to reduce them further. Ultimately, the EIC will be required for precise quantitative studies and to explore the small x_N regime where novel non-linear recombination and saturation phenomena are expected.

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